*Nuclear Reactions on Unstable Nuclei and the Surrogate Reaction Technique**

12-15 January 2004
Asilomar Conference Grounds, Pacific Grove, California

Workshop Program

Monday, January 12

Morning (8.30 am – noon)
Session P: The physics of nuclear reactions
Venue: Heather

Goal: This session will give a general overview of the workshop and provide useful background information to the participants. Emphasis will be placed on the theory of nuclear reactions.

Chair: John Schiffer, Argonne

8.30 *Welcome* – Ed Hartouni, LLNL (15 min)

8.45 *Practical issues* – Workshop Organizers (15 min)

9.00 *Introduction to and overview of the workshop* – Erich Ormand, LLNL (35+10 min)

9.45 *Coffee Break (30 min)*

10.15 *Reaction theory: Statistical aspects* – Mark Chadwick, LANL (40+10 min)

11.05 *Reaction theory: Direct reactions* – Jeff Tostevin, Surrey (40+10 min)

11.55 *Lunch Break*

Afternoon (1.30 pm – 5.10 pm)
Session A: Applications, opportunities, and needs
Venue: Heather

Goal: This session will motivate the study of reactions on unstable nuclei and give a survey of which reactions are important to determine and why. The importance and potential impact of knowing reaction cross sections on unstable nuclei will be discussed. Opportunities at radioactive ion beam facilities will be considered.

Chair: Alan Shotter, TRIUMF, Canada

1.30 *Introductory remarks* – Alan Shotter, TRIUMF, Canada (5+5 min)

1.40 *Nuclear astrophysics, reaction rates, stellar evolution* – Thomas Rauscher, Basel (35+10 min)

2.25 *Nucleosynthesis in stellar explosions* – Jeff Blackmon, ORNL (35+10 min)

3.10 *Coffee Break* (30 min)

3.40 *Direct measurements of radiative capture reactions using radioactive beams: Opportunities for the Surrogate approach* – John D'Auria, TRIUMF and Simon Fraser University (35+10 min)

4.25 *Stockpile stewardship needs for neutron reaction data and the Surrogate reaction method* – Larry Ahle, LLNL (35+10 min)

5.10 *End of Session*

Tuesday, January 13

Morning (8.20 am – 12.10 pm)
Session S: The Surrogate method – Merging theory and experiment
Venue: Heather

Goal: Surrogate techniques for obtaining cross sections for hard-to-determine reactions will be presented and discussed.

Chair: Chip Britt, LLNL

8.20 *Measurements of Asymptotic Normalization Coefficients - an indirect technique for determining capture reaction rates at stellar energies* – Robert Tribble, Texas A&M (35+10 min)

9.05 *Application of the surrogate method to actinide (n,f) cross sections* – Walid Younes, LLNL (35+10 min)

9.50 *Surrogates in the 1970's* – Jerry Wilhelmy, LANL (20+10 min)

10.20 *Coffee Break* (20 min)

10.40 *Surrogate nuclear reactions with STARS at GAMMASPHERE* – Lee Bernstein, LLNL (25+10 min)

11.15 *Surrogate nuclear reactions – The theory effort at LLNL* – Jutta Escher, LLNL (15+5 min)

11.35 *Overview of the Center of Excellence of Radioactive Ion Beam Studies for Stewardship Science* –Jolie Cizewski, Rutgers (25+10 min)

12.10 *Lunch Break*

Afternoon (1.30 pm – 5.00 pm)
Sessions D-I and D-II: Experimental and theoretical details
Parallel Sessions
Venue: Heather and Curlew

See next page.

Evening (5.30 pm – 7.00 pm)
Reception
Light Snacks and No-Host Bar
Venue: Seascape

Afternoon (1.30 pm – 5.00 pm)
Sessions D-I and D-II: Experimental and Theoretical Details
Parallel Sessions
Venue: Heather and Curlew

Goal: The parallel sessions will allow for presentations of experimental and theoretical techniques that can contribute to the development of the Surrogate method.

Session I – Venue: Heather
Chair: Rob Hoffman, LLNL

1.30 *The one-body approximation in nuclear reactions* – Byron Jennings, TRIUMF, Canada (15+5 min)

1.50 *Level densities off the line of stability* – Tom Massey, Ohio University (15+5 min)

2.10 *Comparing the total gamma-ray spectrum for* ^{116}Sn *from the* (^{3}He, α) *and* (n,γ) *reactions* – Undraa Agvaanluvsan, NCSU and LLNL (15+5 min)

2.30 *Nuclear reaction model code EMPIRE* – Mike Herman, BNL (15+5 min)

2.50 *A theorem for two nucleon transfer on radioactive* ^{44}Ti – Larry Zamick, Rutgers (15+5 min)

3.10 *Coffee Break* (30 min)

Chair: Byron Jennings, TRIUMF

3.40 *Particle branching ratio measurements with transfer reactions at intermediate energies* – Barry Davids, TRIUMF (15+5 min)

4.00 *Experimental and theoretical evaluation of* $^{193}Ir(n,n')^{193m}Ir$ *cross section* – Patrick Talou, LANL (15+5 min)

4.20 *Overview of the LLNL experimental effort and measurement of the Surrogate reaction* $^{92}Zr(^{3}He,\alpha/^{3}He)$ – Jennifer Church, LLNL (15+5 min)

4.40 *Preliminary results and status of Surrogate reactions at Yale* – Cristina Plettner, Yale (15+5 min)

5.00 *End of Session*

Session II – Venue: Curlew
Chair: Dennis McNabb, LLNL

1.30 *Development of a lead slowing down spectrometer to measure the fission cross section of* ^{235m}U – Bob Haight, LANL (15+5 min)

1.50 *Developing techniques to measure (d,p) on* ^{132}Sn – Kate Jones, Rutgers (15+5 min)

2.10 *Surrogate cross section measurements in inverse kinematics using radioactive beams: the recyclotron project at the 88 Cyclotron* – Peggy McMahan, LBNL (15+5 min)

2.30 *Oblique-basis shell model method* – Vesselin Gueorguiev, Bulgarian Academy of Sciences and LSU (15+5 min)

2.50 *A new device for measuring reactions in inverse kinematics* – John Schiffer, Argonne (15+5 min)

3.10 *Coffee Break* (30 min)

Chair: tba

3.40 *tba* – Speaker tba

4.00 *tba* – Speaker tba

4.20 *tba* – Speaker tba

4.40 *tba* – Speaker tba

5.00 *End of Session*

5.30 *Social Event* (60+ min)

Wednesday, January 14

Morning (8.30 am – noon)
Session ET: Experimental and theoretical approaches and tools
Venue: Heather

Goal: In this session modern experimental and theoretical approaches and tools for determining reactions on unstable nuclei will be discussed.

Chair: Michael Thoennessen, MSU/NSCL

8.30 *Requirements for determining low-energy neutron radiative capture cross sections by the Surrogate technique* – Frank Dietrich, LLNL (25+10 min)

9.05 *Current status and future developments in understanding the synthesis and reactions of heavy nuclei* – Walter Loveland, Oregon State University (25+10 min)

9.40 *Coffee Break* (30 min)

10.10 *Transfer to the continuum method* – Angela Bonaccorso, INFN, Italy (25+10 min)

10.45 *Role of level densities, level fluctuations and intermediate structure in fission cross-section calculations* – J. Eric Lynn, LANL (25+10 min)

11.20 *Spin distributions in the pre-equilibrium process* – Toshihiko Kawano, LANL (25+10 min)

11.55 *Lunch Break*

Afternoon (1.30 pm – 5.00 pm or later as needed)
Session W: Working Groups
Venue: Heather, Curlew, and Marlin

Goal: The participants will split up into 3-5 groups to discuss particular aspects and questions related to the Surrogate method. Each group will have a designated discussion leader and will be charged with preparing a summary of their findings to be presented to all participants later. Coffee will be served around 3 pm.

Possible issues to be addressed (a selection):

1. **Matching entrance and exit channels:** A compound nucleus can often be formed in two (or more) ways. How do the constants of motion (energy, angular momentum, parity, isospin, etc.) differ from each other in the different entrance channels? How do these differences impact the observed cross sections? Is it possible to extract reliable branching ratios for the decay of the compound nucleus into different exit channels? What experimental data can be provided to help match the entrance and exit channels?

2. **Pre-equilibrium effects:** A central issue in the Surrogate approach is the assumption that a compound nucleus is formed which then decays into various possible exit channels. This assumption has to revisited. In particular, it is necessary to study the role that pre-equilibrium effects play. Under which circumstances can pre-equilibrium contributions be neglected? How well can we estimate these contributions? What reactions minimize pre-equilibrium effects? What sort of experimental studies are needed to advance our understanding of pre-equilibrium decay?

3. **Implementation of the Surrogate method:** What are the tools and ingredients that are necessary to make the Surrogate method work? How reliable and accurate are these tools and ingredients? Some examples: Hauser-Feshbach codes, direct-reaction codes, pre-equilibrium codes, level-density formulae and tables, particle and gamma detector arrays, mass separators, etc.

4. **Applications and limitations:** What are the most suitable areas of application for the Surrogate method? How well can the method be expected to do? What are its limitations? What is the potential use of the method at Radioactive Beam Facilities? How does the Surrogate technique compare to other methods of extracting cross sections involving radioactive nuclei?

Some aspects to be considered when addressing the above issues:

- Evaluation of past and recent work: What has been demonstrated? What are the implications?
- What sort of experimental developments are necessary to make progress?
- What are the theoretical needs? What sort of developments are necessary to make progress?

Thursday, January 15

Morning (8.30 am – noon)
Session O: Overall Summary and Discussion
Venue: Heather

Goal: One individual from each working group will summarize the findings of their group. The results of each group will be discussed. A final presentation will focus on formulating the main conclusions of the workshop, on identifying the most important areas in need of theoretical and experimental development and on outlining strategies for making progress.

Chair: Larry Ahle, LLNL

8.30 *Presentations by Working Group A* – Spokesperson for Working Group A (25+10 min)

9.05 *Presentations by Working Group B* – Spokesperson for Working Group B (25+10 min)

9.40 *Coffee Break* (25 min)

10.05 *Presentations by Working Group C* – Spokesperson for Working Group C (25+10 min)

10.40 *Presentations by Working Group D* – Spokesperson for Working Group D (25+10 min)

11.15 *Summary talk* – John Schiffer, Argonne (35+10 min)

12.00 *Lunch Break and End of Workshop – NOTE: Check-out time is 12.00 noon!*

Afternoon (1.30 pm – 5.00 pm)
Session R: Workshop report
Venue: Oak Knoll 1

Goal: A group of individuals identified prior to the workshop, plus additional interested persons, will prepare a final report of the workshop results. The report will be based on the findings of the individual working groups and might include the transparencies of selected speakers.

Abstracts

Introduction and overview over the workshop
Erich Ormand, LLNL

Reaction theory: Statistical aspects
Mark Chadwick, LANL

I will discuss the statistical theory of nuclear reactions together with relevant applications in nuclear physics and technologies. I shall focus on the Hauser-Feshbach, preequilibrium, and fission theories. I will desribe how theoretical techniques play an important role in understanding measurements made at GEANIE, as well as other measurements that provide insights into the statistical decay process, such as isomeric state production.

Reaction theory: Direct reactions
J.A. Tostevin, University of Surrey, UK

This overview will introduce the essential concepts underlying available modern theoretical direct reaction methods. Available semi-classical, and perturbative and non-perturbative quantum mechanical approaches applicable to low and intermediate incident beam energies will be discussed, including the role and treatment of the excited continuum and resonances in reactions induced by light-ion and exotic and near-dripline projectiles. Fully dynamical, sudden and adiabatic models, hybrid, semi-classical and eikonal, and distorted waves and coupled channels methods will be outlined and contrasted in the context of recent and planned particle transfer, elastic and inelasic breakup etc. experiments using rare radioactive ion beams.

Nuclear astrophysics, reaction rates, stellar evolution
Thomas Rauscher, Basel University, Switzerland

Nucleosynthesis in stellar explosions
Jeff Blackmon, Physics Division, Oak Ridge National Laboratory*

Stellar explosions such as supernovae and X-ray bursts produce energy at a greater rate than almost any other astrophysical phenomenon. The r and p processes that are believed to occur in supernovae are important contributors to the production of heavy elements in the Galaxy. The rp process that occurs in X-ray bursts is important for understanding the composition of neutron stars. Our understanding of the nuclear burning occuring in supernovae and X-ray bursts is hampered by a lack of nuclear data on the short-lived radioactive isotopes that are important in these events. Radioactive ion beams that have been developed at facilities around the world are now beginning to supply some of the important nuclear data needed to better understand stellar explosions. Often novel and indirect experimental techniques are applied in order to overcome difficulties encountered in working with radioactive ion beams. The nuclear data important for understanding nucleosynthesis in supernovae and X-ray bursts will be discussed with emphasis on techniques with radioactive beams and targets, including transfer reactions and the surrogate reaction technique.

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Direct measurements of radiative capture reactions using radioactive beams: Opportunities for the Surrogate approach
John M. D'Auria, TRIUMF and Simon Fraser University, Canada

Experimental measurements of radiative proton and alpha capture reactions directly using radioactive beams and inverse kinematics is now a proven possibility. Such reactions are of importance in understanding element production in explosive stellar scenario. The DRAGON facility at the ISAC RB facility (in Vancouver, Canada) is now operational and has completed its first study, namely the radiative proton capture reaction on ^{21}Na. The main emphasis of this presentation will be to review the capabilities of the DRAGON facility based upon this first study, the planned program using both stable and radioactive heavy ion beams, and a description of what is needed to perform such types of reactions using radioactive beams with reference to specific examples. A brief description of other RB facilities will be given, leading into the question: What can be done directly with present facilities and given the experimental difficulties, what are the opportunities for surrogate reactions?

Stockpile stewardship needs for neutron reaction data and the Surrogate reaction method
Larry Ahle, LLNL

The Stockpile Stewardship community is interested in better neutron cross-section data on a variety of unstable isotopes. This data plays an important role in interpreting nuclear weapon test data. Unfortunately, most of these cross-sections are not experimentally assessable with conventional techniques at the present time due to limitations of target material production and fluxes from neutron sources. While future radioactive ion beam facilities will increase the number of nuclei available for direct measurements, to fully utilize the capabilities of these facilities, new measurement techniques must developed. The Surrogate Reaction Method is such a technique. How this technique can play a role in stewardship measurements now and in the future will be discussed.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Measurements of Asymptotic Normalization Coefficients - an indirect technique for determining capture reaction rates at stellar energies
Robert Tribble, Texas A & M

In order to make progress in understanding stellar evolution, it is important to obtain good information on stellar capture reaction rates. Direct measurements of capture rates have been carried out for many years. But indirect techniques often provide the same information. And they can be invaluable for systems where direct measurements prove to be difficult or impossible. It is well known that direct capture of charged particles in stellar environments occurs at large radii and depends on the normalization of the tail of the nuclear overlap function. We have developed techniques to measure this normalization factor - the asymptotic normalization coefficient (ANC) - which fixes the direct capture rate. ANCs also can be connected to resonance capture and are particularly useful to determine capture rates to subthreshold states. In this talk I will give an overview of the ANC technique, including the connection between ANCs and astrophysical quantities, and discuss the systems where it has been applied. The limitations of the technique will be presented, along with the uncertainties that are inherent in extracting ANCs from nuclear reaction cross sections. Finally future possibilities for ANC measurements will be discussed that include both stable and radioactive beams.

Application of the surrogate method to actinide (n, f) cross sections
Walid Younes and Chip Britt, LLNL

The surrogate-reaction method has been successfully applied to estimate neutron-induced fission cross sections on targets of ^{231,233}Th, $^{230-237,235m,239}$U, $^{236-238,236m}$Np, ^{237,237m,240,241,243}Pu, and $^{240-244,242m,244m}$Am for incident neutron energies of up to ≈ 8 MeV, based on measured (t, pf), $(^3\text{He}, df)$, and $(^3\text{He}, tf)$ data [1,2]. The surrogate technique provides an indirect measurement of (n, f) cross sections on actinide targets too short-lived for a direct measurement. In the present work, measured fission probabilities in the t- and ^{3}He-induced reactions have been fit using a statistical Hauser-Feshbach model, and decomposed as a function of excitation energy, spin, and parity into products of formation probabilities, and reaction-independent fission probabilities. The reaction-independent fission probabilities have been folded with a coupled-channel calculation of the neutron absorption cross section to produce estimates of the (n, f) cross sections. Where data exist, comparisons with direct measurements of the (n, f) cross sections suggest that the present surrogate-technique results are generally accurate to within 20% below incident neutron energies ≈ 1 MeV, and 10% at higher energies. In many cases, (n, f) cross sections have been obtained for actinide targets with half-lives ranging from a fraction of a second to a few days. These cross sections cannot be directly measured by any other means.

The surrogate technique will be reviewed in the context of the present results. The estimated (n, f) cross sections will be presented and compared to direct measurements where available. Planned extensions of this work to higher incident neutron energies will be discussed.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

[1] W. Younes and H. C. Britt, Phys. Rev. C **67**, 024610 (2003).
[2] W. Younes and H. C. Britt, Phys. Rev. C **68**, 034610 (2003).

Surrogates in the 1970's
Chip Britt, LLNL, and Jerry Wilhelmy, LANL

During the 1970s we began to investigate the use of surrogate reactions to simulate neutron induced reactions for what would otherwise be inaccessible target materials for direct neutron studies. The primary interest was on extracting (n,f) cross sections for a variety of actinides. This work was an expansion of early work done by Cramer and Britt [1] who had used d and t projectiles to extract equivalent neutron cross sections for some actinides. The primary improvement of our approach was to expand the method using ^{3}He projectiles. The advantage of these were: new isotopes could be reached, projectile break up issues were less severe, and higher nuclear excitation energies could be reached. The Los Alamos Van de Graaff facility was used for the accelerator and we made extensive use of the LANL ability to produce suitable target materials for many actinides. Results were published [2,3]. In addition to equivalent (n,f) reactions we also attempted to determine simulated (n,α) and (n,p) in the A=90 region. Some examples from these studies will be presented along with a discussion of the early realization of the limitations of the surrogate technique with regard to entrance channel effects associated with angular momentum differences and preequilibrium particle emission.

This work was performed in part under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

[1] J.D. Cramer and H.C. Britt, Nucl. Sci. Eng **41**,177(1970).
[2] J.B. Wilhelmy et.al., Proc. conf. Nuclear Cross sections and Technology, NBS Special Publication **425**, 218 (1975).
[3] H.C. Britt and J.B. Wilhelmy, Nucl. Sci.Eng. **72**, 222 (1979).

Surrogate nuclear reactions with STARS at GAMMASPHERE
Lee Bernstein, LLNL

The LLNL experimental nuclear physics group has developed a new high-resolution particle spectrometer for use in surrogate reaction measurements called STARS (Silicon Telescope Array for Reaction Studies). In this talk I will discuss the first experiment using STARS coupled to the GAMMASPHERE γ-ray spectrometer to determine the validity of the surrogate reaction method by comparing the decay of excited ^{156}Gd and ^{157}Gd formed using the ^{157}Gd(^{3}He,α)^{156}Gd* and ^{157}Gd(^{3}He,^{3}He)^{157}Gd* reactions to their decay following neutrons on ^{155}Gd and ^{156}Gd respectively. Results from the experiment will be compared to model calculations and competition between equilibrium and pre-equilibrium reaction modes discussed. The new experimental program using STARS coupled to the YRAST-ball γ-ray spectrometer at the Wright Nuclear Structure Laboratory at Yale University will also be presented.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Surrogate nuclear reactions – The theory effort at LLNL
Jutta Escher, LLNL

The Surrogate reaction technique can be employed to estimate reaction cross sections that cannot be measured directly. This is particularly relevant for reactions involving unstable nuclear species. The successful application of the Surrogate technique requires models that relate the reaction of interest to an alternative ('Surrogate') reaction which proceeds through the same compound system. Initial, limited, applications of the method in the rare earth and actinide regions show promise. In order to extend the applicability of the technique, new and improved theoretical tools and models become necessary. Efforts are underway at LLNL to provide a comprehensive framework for planning and analyzing Surrogate experiments. The applications will focus particularly on reactions involving unstable nuclei that play a key role in the production of the elements between iron and uranium. A brief overview over the theoretical "Surrogate Nuclear Reactions" program at LLNL will be given. The main challenges to be addressed will be outlined and possible applications will be considered.

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Overview of the Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science
Jolie A. Cizewski, Rutgers University

The Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science is a collaboration of nuclear scientists from Rutgers University, the University Radioactive Ion Beam (UNIRIB) consortium, Oak Ridge national Laboratory, and Livermore and Los Alamos National Laboratories that focuses on experimental studies that would provide information on nuclear cross section information on fission fragments or isotopes of importance as radiochemical detectors in nuclear devices. The measurements are conducted at the Holifield Radioactive Ion Beam Facility at Oak Ridge National laboratory using radioactive ion beams to enable light-ion transfer reactions. The present talk would give an overview of the activities of the Center. Subsequent talks will discuss in detail the initial measurements, prospects for future measurements, and the tools that are being developed as part of the activities of this Center.

The one-body approximation in nuclear reactions
Byron K. Jennings, TRIUMF, Canada

The use of a spectroscopic factor can be considered a prototype for the use of information from one type of reaction to related reactions – a hallmark of the surrogate reaction technique. The role and nature of the one-body approximation is explored with special emphasis on the role of the spectroscopic factor. Particular attention is paid to proton emission and radiative capture. The role of the spectroscopic factor is clear in radiative capture but ambiguous in proton emission.

Level densities far from stability
Tom N. Massey, Ohio University

We have recently completed studies of all nuclei with known levels with 20<A<100. The level densities were studied as a function of A and Z-Z_0, where Z is the nuclear charge and Z_0 is the equilibrium charge for a given mass. These studies indicated that the level density will be lower off the line of stability based on the know levels at low excitation energy. This formulation of the level densities has been incorporated in the Hauser-Feshbach program, HF2002. Work is now in progress for a series of experiments to investigate the dependence of nuclear level densities off of the line of stability at higher excitation energies. Current plans call for measurements using the (^{3}He,n) reaction, (^{12}C,p) and (^{12}C,α). Future investigation are planned using radioactive beams and a carbon target.

This work was supported under U.S. D.O.E. grant No. DE-FG02-88ER40387.

Comparing the total gamma-ray spectrum for ^{116}Sn from the (^{3}He, α) and (n,γ) reactions
Undraa Agvaanluvsan, North Carolina State University and LLNL

The level density and radiative strength functions for 116Sn are extracted experimentally from the primary gamma rays after a light-ion reaction. The decay probability of primary gamma rays is proportional to the product of the level density and radiative strength function. In this talk the extraction method is outlined and the normalization of the level density and radiative strength function is explained. The resulting level density and radiative strength function are used to obtain the total gamma ray spectrum and compared with the one obtained directly from the (n,gamma) reaction.

This work was performed in part under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Nuclear reaction model code EMPIRE
Mike Herman, National Nuclear Data Center

EMPIRE-II belongs to a new generation of nuclear reaction codes, and is intended as a general theoretical tool to be used in basic research and nuclear data evaluation for the calculation of nuclear reactions over a broad range of incident energies and projectiles. The code contains up to date nuclear reaction models and is very easy to use. EMPIRE-2.18 (Mondovi), which is currently available, includes major nuclear reaction mechanisms, such as optical model (SCAT2), coupled channels (ECIS), Multistep Direct (ORION + TRISTAN), NVWY Multistep Compound, Monte Carlo pre-equilibrium emission DDHMS, exciton model (DEGAS) and the full featured Hauser-Feshbach model with widths fluctuation correction. The 2.19 (Lodi) version (to be released soon) will improve treatment of the fission channel and allow for preequilibrium emission of clusters. A comprehensive library of input parameters covers nuclear masses, optical model parameters, ground state deformations, discrete levels and decay schemes, level densities, fission barriers (BARFIT), moments of inertia (MOMFIT), and gamma-ray strength functions. Calculated results can be converted into the ENDF-6 format using an accompanying code EMPEND. The package includes full EXFOR library of experimental data, which are automatically retrieved during calculations. By default, plots comparing experimental results with the calculated data are produced using improved PLOTC4 code. Interactive plotting is possible through a powerful ZVView package. Simple operation of the whole system is ensured by the graphic user interface.

Flexibility, extensive coverage of nuclear reaction mechanisms, detailed modeling of the gamma-cascade and capability of predicting isomeric cross sections make EMPIRE-II an ideal tool for theoretical support of the surrogate reaction technique.

A theorem for two nucleon transfer on radioactive ^{44}Ti

Larry Zamick, Rutgers

In the single j shell approx the wave function of a state in ^{44}Ti can be written as $\sum_{J_p,J_n} D(J_p,J_n)[(jj)J_p(jj)J_n]$ where D is the probability amplitude that protons couple to J_p and neutrons to J_n. For the $J=0$ ground state $J_p=J_n$. As an example for one realistic interaction $D(0,0)=.7878$, $D(2,2)=.5617$, $D(4,4)=0.2208$ and $D(6,6)=0.1234$. We calculate the number of pairs of angular momentum J_{12}, when 2 nucleons (2 neutrons or 2 protons or one neutron and one proton) are removed from ^{44}Ti. and compare our results with the case where no interaction os present.The number of pairs with J_{12}=0 for these two limits are (1.862,0.75) i.e. the interaction efffects are such as to enhance the number of J_{12} pairs. For J_{12}=1 the numbers are (0.675,0.412), also an enhancement.The number of pairs with J_{12}=2 and 7 are also increaesd but the others (J_{12}=3,4,5,6) are decreased. The expression for the number of pairs of angular momentum J_{12} is $2|D(J_{12},J_{12})|^2 = |F(J_{12})|^2$, where $F(J_{12}) = 2\sum_J D(J,J)\langle(jj)J(jj)J|(jj)J_{12}(jj)J_{12}\rangle$ where the latter factor is a unitary nine-j symbol. Our theorem relates to the fact that if J_{12} is even the above expression for the number of pairs simplifies to $3|D(J_{12},J_{12})|^2$. We seem to get such a simple result only fot the N=Z nuclei which tend to be unstable as we go up in mass, so we appreciate the fact that new tecniques will make nuclear structure calculations of this kind more meaningful.

Particle decay branching ratio measurements with transfer reactions at intermediate energy

Barry Davids, TRIUMF, Canada

Resonant contributions to astrophysical reaction rates can be measured directly in the laboratory provided the beam and target are available and the resonance strength is great enough that appreciable yield can be obtained in a reasonable amount of time. Alternatively, one can measure the decay widths of a resonance populated in a transfer reaction. By combining a measurement of the particle decay branching ratio with a lifetime measurement, one obtains equivalent information. I will describe measurements of alpha particle and proton decay branching ratios made using transfer reactions at intermediate beam energies relevant to alpha and proton captures in novae and x-ray bursts.

Experimental and theoretical evaluation of $^{193}Ir(n,n')^{193m}Ir$ cross section

P. Talou[1], M.B. Chadwick[1], R. Nelson[2], N. Fotiades[2],
M. Devlin[2], P.E. Garrett[3], W. Younes[3], and J.A. Becker[3]
[1] **T-16, Nuclear Physics Group, Los Alamos National Laboratory**
[2] **LANSCE-3, Los Alamos National Laboratory**
[3] **N-Division, Lawrence Livermore National Laboratory**

Neutron-induced reactions on Iridium isotopes are often used as radiochemical detectors to infer neutron fluences. Due to the presence of isomers and unstable ground-states in the Iridium chain, the neutron spectrum can be probed in various energy regions, e.g., $(n,2n)$ reactions are sensitive to the 10-20 MeV region, while (n,n') reactions are most influenced by few-MeV neutrons.

The excitation function of $^{193}Ir(n,n')^{193m}Ir$ has recently been measured with the GEANIE γ-rays detector at LANSCE. However, only a fraction of this cross section could be obtained through γ-rays detection, and theoretical modeling was used to infer the missing contributions. The statistical and preequilibrium nuclear reaction code GNASH was first tested against partial GEANIE data, and then used to infer the total isomer cross section.

This work can be seen as an example of the surrogate concept in the sense that the measurements do not probe directly the reaction cross section of interest, but instead provide a partial answer before relying on theoretical modeling to infer the final result. This is a very good example on how theory and experiment can directly benefit from each other.

This work was performed in part under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Overview of the LLNL experimental effort and measurement of the Surrogate reaction $^{92}Zr(^3He,\alpha/^3He)$

Jennifer Church, LLNL

The LLNL experimental program for measuring surrogate nuclear reaction cross sections has begun recently at Yale University's Wright Nuclear Structure Laboratory. These experiments utilize STARS (Silicon Telescope Array for Reaction Studies) in conjunction with germanium clover detectors from the YRAST-ball γ-ray spectrometer. The first experiment of the program, the reaction $^{92}Zr(^{3}He,\alpha/^{3}He)$ as a surrogate for neutrons on ^{90,91}Zr, has already been performed, and the second experiment, $^{238}U(p,p/d/t)$ surrogate reactions for n + $^{235-237}U$, is scheduled for April. The overall program will be outlined and experimental details of the $^{92}Zr(^{3}He,\alpha/^{3}He)$ measurement discussed.

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Preliminary results and status of Surrogate reactions at Yale

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The STARS (Silicon Telescope Array for Reaction Studies) commisioning experiment was performed at the Wright Nuclear Structure Lab at Yale University past November. In addition to the charged particle identification performed by STARS, the detection of the gamma rays was achieved by using theYRAST ball, comprising four clover detectors. The used ^{3}He-induced reactions serve as surrogates for the ^{90,91}Zr(n,xγ) reactions. Some insights in the data analysis will be given: the time and energy spectra discussed, as well as the correlation front-back Si detectors. The data analysis is in progress.

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Development of a lead slowing down spectrometer to measure the fission cross section of ^{235m}U

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A Lead Slowing-Down Spectrometer (LSDS) is being developed to measure the fission cross section of the isomeric state of ^{235}U, the 26-minute half-life excited state at $\sim$77 eV. Calculations say that this state can be populated significantly by inelastic scattering of energetic neutrons. Preliminary calculations of the isomers fission cross section indicate significant differences compared to the ground state cross section below an incident neutron energy of 500 keV. It is believed that surrogate reactions are not suitable for deducing the differences in the fission cross sections of the isomer and the ground state in this energy region and therefore a direct measurement is required. The LSDS is based on a 20-ton cube of lead, consisting of 36 individual modules, on loan from the French CEA laboratory at Bruyres-le-Chtel. Channels in this assembly allow for the 800 MeV proton beam from the LANSCE Proton Storage Ring to produce a pulsed spallation neutron source in the center of this cube. Fission chambers and other detectors placed at different locations in the cube quantify the expected relationship between time and the mean neutron energy below 100 keV, $E_n = K/(t+t_o)^2$. The flux at the fissionable samples is expected to be about a factor of 1000 more than available elsewhere. The ^{235}U isomer can be prepared by separating it from ^{239}Pu, which decays by alpha emission primarily to this state, the steady state ratio being 2×10^{-9}. Progress in characterizing the LSDS and in planning for the separation of the isomer will be described.

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Developing techniques to measure (d,p) on ^{132}Sn

Kate Jones, Rutgers University

The recent advent of intense neutron-rich fission fragment beams at the HRIBF at ORNL has provided the opportunity to perform neutron transfer reactions in inverse kinematics around the doubly magic ^{132}Sn, to measure l-values and spectroscopic values. Such measurements can provide input into neutron-capture reaction rates of interest for stewardship science. We will present the results from a test experiment using the stable beam ^{124}Sn to illustrate the technique which we propose to utilize to measure states in ^{133}Sn and other neutron-rich fission fragments.

Oblique-basis shell model method
Vesselin Gueorguiev, Bulgarian Academy of Sciences and LSU

The study of a complex system with two or more different modes can be enhanced by using mixed-mode basis states in the strongly coupled limit of the system. A toy model of a harmonic oscillator in a one-dimensional box will be used to illustrate the oblique-basis idea. Applications to nuclear structure will be discussed within the nuclear shell model.

A new improved method for studying transfer reactions in inverse kinematics
John Schiffer, Argonne

Reactions in inverse kinematics at the energies appropriate for transfer reactions are difficult at present and because of 'kinematic compression' require large detection arrays with fine segmentation and thin targets to obtain good resolution and particle identification is cumbersome. In a uniform magnetic field (a solenoid co-axial with the beam) the detector arrays are much more compact, particle identification by time of flight becomes easy, and the effective resolution between final states is improved substantially.

Requirements for determining low-energy neutron radiative capture cross sections by the Surrogate technique
Frank Dietrich, LLNL

Radiative neutron capture on unstable nuclei at low energies (up to roughly 100 keV) is important for astrophysics and other applications but is difficult to calculate accurately. Making an indirect measurement by using the surrogate technique to populate the compound nucleus just above the neutron separation energy is promising. However, this technique has special problems because the energy resolution of the particle that tags the energy of the compound nucleus is insufficient to determine the compound nuclear energy to better than 25-100 keV in typical cases. A possible strategy to overcome this difficulty is to assume that calculations can adequately describe the energy dependence of the capture cross section, and to use the surrogate technique to normalize the scale of the cross section at somewhat higher energies (100-400 keV). The assumptions underlying this strategy will be examined, using results from a current study of capture on actinide nuclei as an example.

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Current status and future developments in understanding the synthesis and reactions of heavy nuclei
Walter Loveland, Oregon State University

The cross section for the production of a heavy evaporation residue, σ_{EVR}, can be written as: $\sigma_{EVR} = \sigma_{CN} W_{sur}$ where σ_{CN} is the complete fusion cross section and W_{sur} is the survival probability of the completely fused system. The complete fusion cross section can be written as $\sigma_{CN} = \sum_{J=0}^{J_{max}} \sigma_{capture}(E_{cm}, J) P_{CN}(E_{cm}, J)$, where $\sigma_{capture}$ is the capture cross section and P_{CN} is the probability that the projectile target system will evolve, inside the fission saddle point to form a completely fused system rather than reseparating (quasi-fission). For reactions involving the heavy elements, $\sigma_{capture}$ is relatively well understood but the factors P_{CN} and W_{sur} are not so well understood. Semi-empirical calculations of P_{CN} and W_{sur} allow one to describe the bulk of the data on heavy element synthesis except for the physics behind the reports of the synthesis of elements 112,113, 114, 115, 116 and 118 in hot fusion reactions. (The same calculations allow us to predict heavy element production rates with RIA). We have undertaken a program of experimental measurements of P_{CN} and W_{sur} for nuclei with 102 $<$ Z $<$ 108 using hot fusion reactions, in hopes of clarifying his situation. Wsur is measured by measuring evaporation residue cross sections and neutron multiplicities in sets of linked cross bombardments that allow the deduction of Γ_n/Γ_f for single members of a chain of excited nuclei. (An extension of these measurements using surrogate reactions to induce fission is underway for U, Np, Pu, Am, Bk, and Cm nuclei whose neutron multiplicities are measured). Special attention is given to element 112 and its production in the ^{48}Ca + ^{238}U reaction.

Transfer to the continuum
Angela Bonaccorso, INFN, Italy

The transfer to the continuum method allows to calculate energy spectra for neutron transfer between an initial bound state to a final continuum states including final state interaction with the final nucleus. The final state is trated via an optical model wave function. The corresponding S-matrix is calculated with an energy dependent optical potential. In this way the elastic scattering component and the absorption component of the neutron re-scattering on the final nucleus are treated consistently and at the same time. For each final continuum energy a sum over all possible final angular momenta is performed. Both single particle isolated and/or overlapping resonances can be discussed.

The role of intermediate structure, level fluctuations and level densities in fission cross-section calculations
J. Eric Lynn, Group T-16, Los Alamos National Laboratory

In theoretical evaluation of neutron cross-sections of the actinides the information on fission barrier heights of the compound nucleus that can be obtained from particle-transfer induced fission reactions can be of vital importance. Because it is the sub-barrier and near-barrier excitation energy regions that are most important for this it is necessary to model realistically the role of cross-section intermediate structure and its fluctuations, and this also applies to the evaluation of neutron cross-sections. Methods of doing this are described. It is shown, with examples, how these effects can be very significant in changing the barrier height analysis and in calculations on neutron cross-sections. Level densities as a function of deformation are of major importance for neutron fission cross-sections at higher energies, and also affect cross-sections at near barrier energies. Some considerations of pairing effects and spin dependence in level densities and the effects on cross-sections are discussed.

Spin distributions in the pre-equilibrium process
Kawano Toshihiko, T16, Los Alamos National Laboratory

An interpretation of surrogate nuclear reaction measurements requires a modeling of reaction process. It is often assumed that the dominant process is a compound reaction, and the Hauser-Feshbach statistical model is used to calculate decay of intermediate compound state. When the incident energy is high, a pre-equilibrium particle emission occurs before the composite system equilibrates, and this changes the spin distribution of compound nucleus slightly.

In the classical framework such as the exciton model it is impossible to calculate the spin distribution of pre-equilibrium process, however, quantum mechanical approaches — FKK, TUL, NWY — can give it. We calculate the quantum mechanical pre-equilibrium theory to estimate the spin-distribution of the doorway state, and investigate how this distribution is important for the surrogate reaction technique.

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